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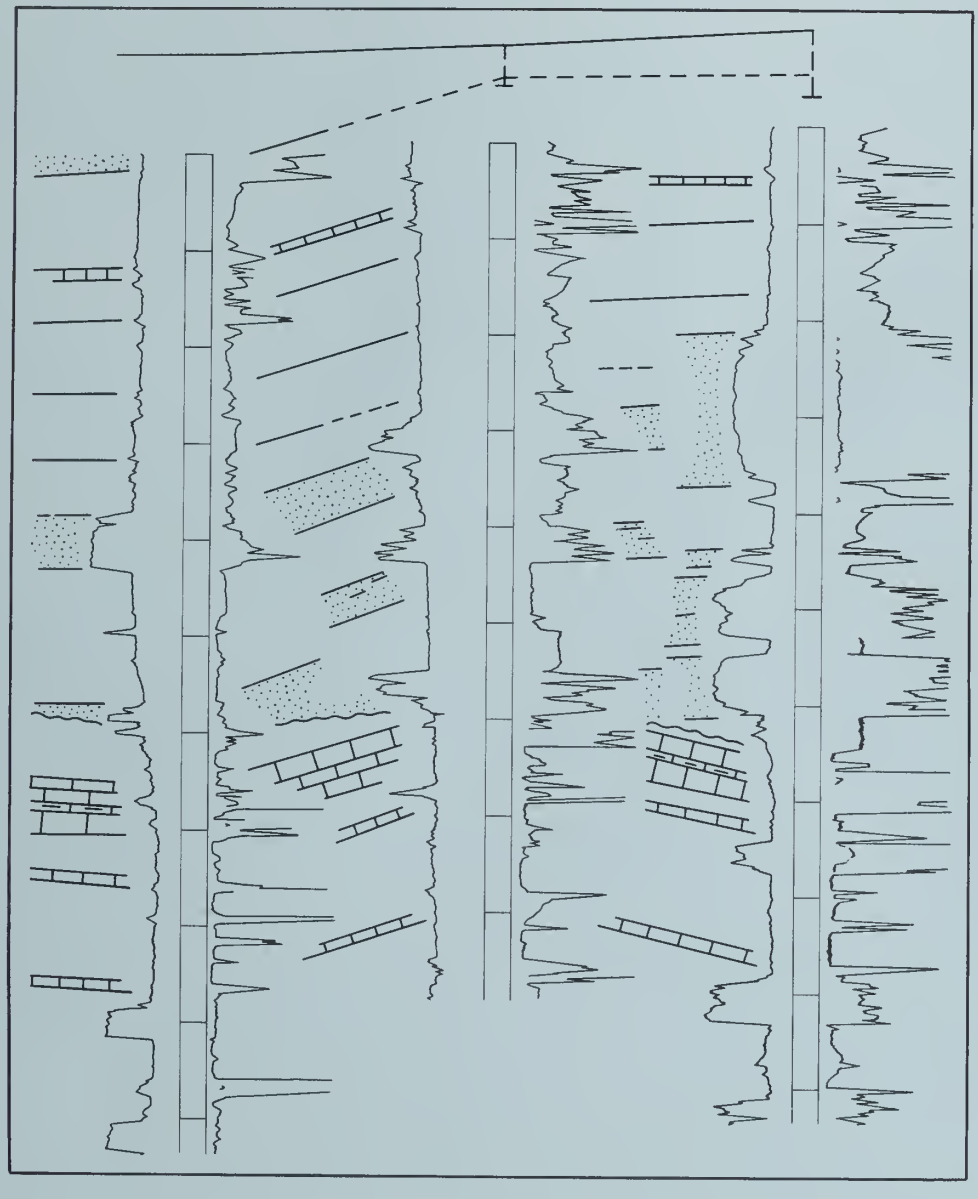
MEASURING COAL SEAM THICKNESSES WITH NORMAL-LATERAL ELECTRIC LOGS

Dwain Berggren



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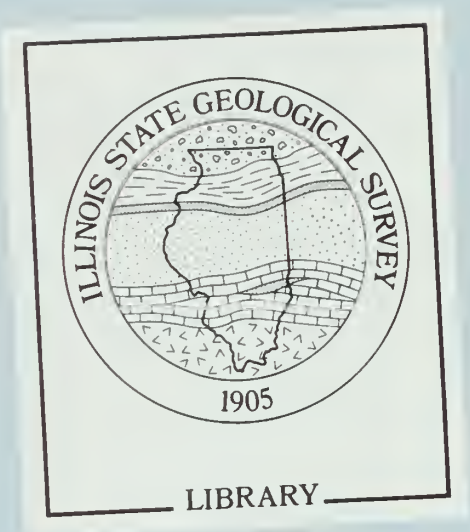

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Cover Typical electric-log cross section of Pennsylvanian and Mississippian units in Illinois.

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GLOSSARY

AM (or AMN) device	short-normal device
AM spacing	distance between the current electrode (A) and the measuring electrode (M) on a short-normal device
AM′ device	long-normal device
AM′ spacing	distance between the current electrode (A) and the measuring electrode (M′) on a long-normal device
AO spacing	distance referred to as the "spacing" of a lateral device; the distance between the measure point (O) of a lateral device and the second electrode uphole from it
bed base	bottom surface of a rock bed or coal seam
centerline	apparent horizontal midline through a normal curve for a rock bed or coal seam
inflection point	point on a curve's limb at which the slope changes sign (or goes from concave to convex)
ON	distance between the measure point (O) and the adjacent downhole electrode on a lateral device

ABSTRACT

This study reviews logging literature and examines log interpretation practices and the Pennsylvanian sections of normal-lateral electric logs from several southern Illinois counties. Methods are recommended for measuring coal seam thicknesses from spontaneous potential, short-normal, long-normal, and lateral curves. As many as 17 features of these curves can mark the top, center, and base planes of a seam, although not all of these features will be present on a given log and not all of those marking the same plane will match perfectly. Measurements are most accurate if taken from the well-defined top-marking and base-marking features of the same normal curve. Less accurate measurements result from doubling a half-bed (centerplane to base or top) measurement on the same curve or from doubled half-bed measurements made between two different curves.

Normal-lateral electric logs comprise about 65 percent of the geophysical logs in the Basic Well Data File of the Illinois State Geological Survey. They are the primary source of coal data in those areas of Illinois where potentially minable coals lie below the ordinary depths of exploration and mining. Although normal-lateral electric logs have been used for coal stratigraphic work since about 1940, major coal resource studies on coal seam thicknesses estimated from electric logs were not published until 1968. Questions persist about how to measure and estimate coal seam thicknesses from the logs and about the reliability of the data.

The methods examined in this study have several advantages. Identifiable features of the normal-lateral electric log curves for a coal seam serve as reference points for measurements. Characteristics of the features and the measurements made from them can be used to judge the reliability of the thickness measurements. The methods moderate interpreter biases that tend to arise from the thinner-than-bed appearance of normal curve bodies, the influence of coal thickness data from adjacent outcrops and core tests, and individual styles and skills.

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INTRODUCTION

Geophysical logs have been used for about 50 years to identify and map Illinois coal resources. Most of the logs available for these studies are normal-lateral electric logs (E-logs) of oil well surveys. In fact, this type accounts for about 62,000 (65%) of the nearly 95,000 geophysical well logs entered through July 1991 in the computerized log files of the Illinois State Geological Survey (ISGS) (Huff, personal communication, ISGS, 1991). In wide areas of central and southern Illinois where minable coals lie below the ordinary depths of coal mining and exploration, normal-lateral E-logs constitute a large, invaluable source of coal data.

Normal-lateral E-logs are records that combine the trace of a spontaneous potential device with the traces of normal devices or with the traces of lateral devices or with both. Several trademark names identify them: Electrical Log (Schlumberger), Electrolog (Lane Wells and Dresser Atlas), and Electric Log (Halliburton and Birdwell). The company names inspired the informal terms electric log and E-log, which are commonly applied not only to the type, but also to other kinds of geophysical logs. In casual usage, "electric log" can be virtually synonymous with wireline log and geophysical log, and in a somewhat stricter sense is understood to designate the records of all the resistivity-measuring devices that conduct or induce electric current into the well-bore fluids and rock. In this study, the term normal-lateral E-log is used to avoid company names and the ambiguities of the informal terms.

The French engineers Conrad and Marcell Schlumberger developed a wireline logging device and recorded the first resistivity log in France in 1927. Their technique, which they at first called electrical coring, used an inverted lateral device to measure the resistivity of rock beds penetrated by wells and test holes. The Schlumberger firm introduced electric logging into United States oil and gas fields in 1929 (Frank 1986). By 1931, the Schlumberger brothers had investigated the spontaneous potential effect in well bores and developed the spontaneous potential device (Schlumberger et al. 1934b). They introduced the short-normal resistivity device and the ordinary lateral device in 1932 and the long-normal (or third-curve) device in 1934 (Hilchie 1979). Logging companies participated in the development of the Illinois Basin oil fields in the late 1930s, and by about 1947, the Schlumberger firm and its competitors had standardized their logs to make the four-trace modern form common in the Illinois Basin: a log bearing spontaneous potential, short-normal, long-normal, and lateral traces in two or three tracks.

In Illinois, the old electric logging methods were gradually replaced after the 1950s by new techniques using induction, radiation, sonic, focused-current, and pad-electrode devices.

The typical normal-lateral resistivity logs are not as suitable as other types for differentiating between coal and other resistive beds, detecting thin beds, and closely measuring coal seam thicknesses. Over the decades, the problem of measuring coal seam thickness with these logs has been of special interest as regional studies of Illinois coal resources have been extended to evaluate the deep-lying, little-explored coals of the Illinois Basin.

This study reviews existing interpretive practices, well logging literature, Illinois coal resource studies, and a selection of normal-lateral E-logs. Methods are recommended by which seam thickness measurements can be made more accurately from the logs and their reliability better judged.

PREVIOUS STUDIES

The earliest Schlumberger papers published in the United States (1934a,b) discussed using the company's resistivity logs in France and the Donetz Basin to detect coal seams missed or indefinitely expressed by driller logging and by sample and core studies.

The ISGS made the first large-scale effort to measure Illinois coal resources with normal-lateral E-logs. The ISGS Control Well Project, conducted from 1941 to 1945, investigated the subsurface geology and coal resources of the Pennsylvanian System in the Illinois Basin (ISGS 1944 1951, Cady 1952). Field crews from the ISGS Coal Section observed rotary drilling operations at 241 oil exploration wells distributed across most of the southern half of Illinois and made very accurate drilling time logs and cutting sample collections (Cady 1952). The drilling time and sample study logs were used to identify key coal and limestone beds and to correlate them with spontaneous potential and normal curves on E-logs from the same wells. (The lateral device was seldom used at this time in Illinois.) The 1944 progress report of Taylor et al. correlated coal seams and other Pennsylvanian key beds identified in local outcrops, cores, and sample studies with specific spontaneous potential, short-normal, and long-normal resistivity curves on E-logs throughout the region.

In the same progress report, Sims et al. (1944) published small-scale thickness maps of the Herrin and Springfield coals in Wayne County. They compiled their maps by estimating seam thicknesses in whole feet from normal curves on several hundred E-logs, which they interpreted by comparing them to the E-logs, drilling time logs, and sample logs of the 26 ISGS control wells in the county. Aside from noting that a reversed normal curve indicated that a seam's thickness was less than the device's AM electrode spacing (Taylor et al. 1944), Sims et al. described no other method of measuring or estimating coal seam thickness from E-log curves and reported estimated thicknesses ranging from 1 to 10 feet in 1-foot intervals.

After 1944, reports based on the ISGS Control Well Project did not attempt to use E-logs to estimate coal seam thicknesses. In 1951, the project director G. H. Cady stated: "After much study . . . it is apparent that the electric logs do not generally provide a satisfactory record of coal bed thickness or of the thickness of accompanying thin beds of black shale, limestone and underclay" (ISGS 1951). He repeated this judgment in his authoritative Bulletin 78, Minable Coal Reserves of Illinois (1952): "Although electric logs may strongly suggest that a coal bed is present, they give unsatisfactory evidence of the thickness of coal beds, so [they] have not been used to delimit areas of this or higher classes of reserves [I-A, Proved; I-B, Probable; II-A, Strongly Indicated]." Without explicitly stating the point, Cady apparently defined the geologic criteria for class II-B, weakly indicated reserves, in a way that permitted the use of electrical logs for this resource classification (table 1).

Trescott (1964) used 1,275 E-logs to map the thickness of the Springfield Coal as part of his study of sedimentation between the Houchin Creek and the Springfield Coals in a nine-township area that includes central and southern Edwards County. Lacking coal data from mines, cores, and outcrops, he compared drilling time and sample logs from ISGS control wells and a few other oil and gas tests to corroborate his correlations and measurements on the E-logs he used. He took coal seam thicknesses directly from the regular short-normal curves with a method he himself devised. Examining a seam curve's two limbs, he picked the points at the left ends of their straight parts (where they begin to curve to meet the shale line) and measured or estimated the vertical footage between them. From this footage, he subtracted 1 foot to obtain the seam's estimated thickness. He provided no technical rationale for his method. Trescott's E-log study is significant because he demonstrated, perhaps for the first time, that a methodical analysis of E-logs from closely spaced holes yields data sufficient to map coal

Table 1 A 1952 ISGS coal resource classification (Cady 1952, table 1).

Class	Maximum distance from datum points*	Accepted datum points	Remarks
I-A Proved	0.5 mile	Mined-out areas, diamond drill holes, outcrops	Approximately equivalent to "measured" category of the USGS
I-B Probable	2 miles	All points of class I-A plus coal test churn drill holes	Approximately equivalent to "indicated" category of the USGS
II-A Strongly Indicated	4 miles	All points of classes I-A and I-B plus churn drill holes drilled for oil or water with unusually good records and control rotary drill holes	Approximately equivalent to "inferred" category of the USGS
II-B Weakly indicated	Indefinite	All points used in higher categories plus knowledge of geologic probability based on all available information	Approximately equivalent to "inferred" category of the USGS
Thin or absent		All available data plus knowledge of geologic probability	Data, though sometimes sparse, show coal thin or absent
No Information			

*Distances modified in practice by geologic considerations.

thicknesses in small intervals (2 feet in his study) and to reveal the systematic relationship of coal thickness to the variations in thickness of the underlying sediment units.

Hopkins (1968) used normal-lateral E-logs to map the thickness and structure of the Springfield Coal (then called the Harrisburg Coal) in the Fairfield Basin of Illinois. The Fairfield Basin is largely the deep Illinois Basin area described previously by the reports developed from the ISGS Control Well Project and Trescott's 1964 study. Although Hopkins cited Trescott's work as "an important contribution to the study of the No. 5 Coal," he chose not to use Trescott's method to estimate coal seam thicknesses on E-logs. Nor did he employ a method described by the technical logging literature discussed in his report: measurement from the inflection points on a regular (right-deflected) normal curve for a seam (Schlumberger Well Surveying Corporation 1958).

Hopkins' method involved two observations. Like his predecessors, he noted the reversed and unreversed deflections of the long-normal and short-normal curves to determine whether a given seam's thickness was (1) less than the short-normal spacing, (2) between the short-normal and long-normal spacing, or (3) greater than the long-normal spacing. In addition, he estimated the seam's thickness directly from the log by eye: "by comparison of the resistivity peaks with the footage marks on the log" (Hopkins 1968, p. 7). Acknowledging the imprecision of coal resource estimates made from electrical logs, he made his estimates in whole feet and did not attempt to estimate thicknesses of less than 3 feet. He did not assign the estimated resources he mapped to ISGS coal resource reliability classes.

In 1975 Allgaier and Hopkins, using Hopkins' earlier (1968) method to obtain thickness data from more than 4,100 E-logs, published a thickness map of the Herrin Coal in the Fairfield Basin. The term reserves used in their report is synonymous with the category of identified resources adopted by the U.S. Bureau of Mines and the U.S. Geological Survey (Allgaier and Hopkins 1975).

Both the 1968 and 1975 reports were major studies that mapped potential coal resources, low-sulfur coal deposits, and coal cutouts; illustrated other details of stratigraphy; and in general validated these applications of E-log data.

Subsequent reports have used Hopkins' method to measure coal resources with normal-lateral E-logs. Treworgy (1981) examined more than 1,500 geophysical logs—mostly normal-lateral E-logs from oil test holes—to map the resources of the Seelyville Coal in eastern and central Illinois. His discussion of methods describes the coal's appearance on various kinds of logs. Nance and Treworgy (1981) used normal-lateral E-logs and other types to compile their strippable coal resource study of Illinois Area 8, the very large central province generally inside the Springfield and Herrin strippable coal areas. A remarkable feature of their study is a plate showing an 84-mile-long, north-south cross section. Most of the logs in it are normal-lateral E-logs reproduced with their lateral traces and demonstrating the use of the excellent thin-bed response of the lateral to correlate some of the very thin, obscure coal seams in the Bond and Mattoon Formations of the Pennsylvanian System.

Jacobson (1983) used normal-lateral E-logs to identify deposits of Murphysboro Coal in the subsurface along a 25-mile reach of the Oraville paleochannel in Jackson and Perry Counties. Noting that "uncertainties of about ±1 foot for thickness estimates are probable" in his coal seam measurements off the log curves, he used about 100 E-logs to extend his mapping of unclassified coal thickness and potential low-sulfur resources away from mine and core data in the coal's outcrop area.

Most of the data used in Jacobson's 1985 study of coal resources in Grundy, Livingston, and La Salle Counties were taken from E-logs and gamma-density logs. He classified the coal resources mapped as class II: strongly indicated (table 2).

A workshop taught by Colin Treworgy at the 1987 Illinois Mining Institute provided the only recent systematic review of the methods used at the ISGS to interpret the more common geophysical logs for coal resource studies.

Table 2 A 1985 ISGS coal resource classification (Jacobson 1985, table A1).

Class	Maximum distance from datum points*	Accepted datum points	Remarks
I Proved and probable	2 miles	Mined-out areas, diamond drill holes, outcrops, coal tests, drill holes	Approximately equivalent to the "measured" and "indicated" categories of the USGS (includes I-A and I-B of Cady 1952)
II Strongly indicated	4 miles	All points of class I plus holes that have unusually good records; interpretations of conventional electric logs and gamma-density logs	Approximately equivalent to the "inferred" category of the USGS (includes only II-A of Cady 1952)

*Distances modified in practice by geologic considerations.

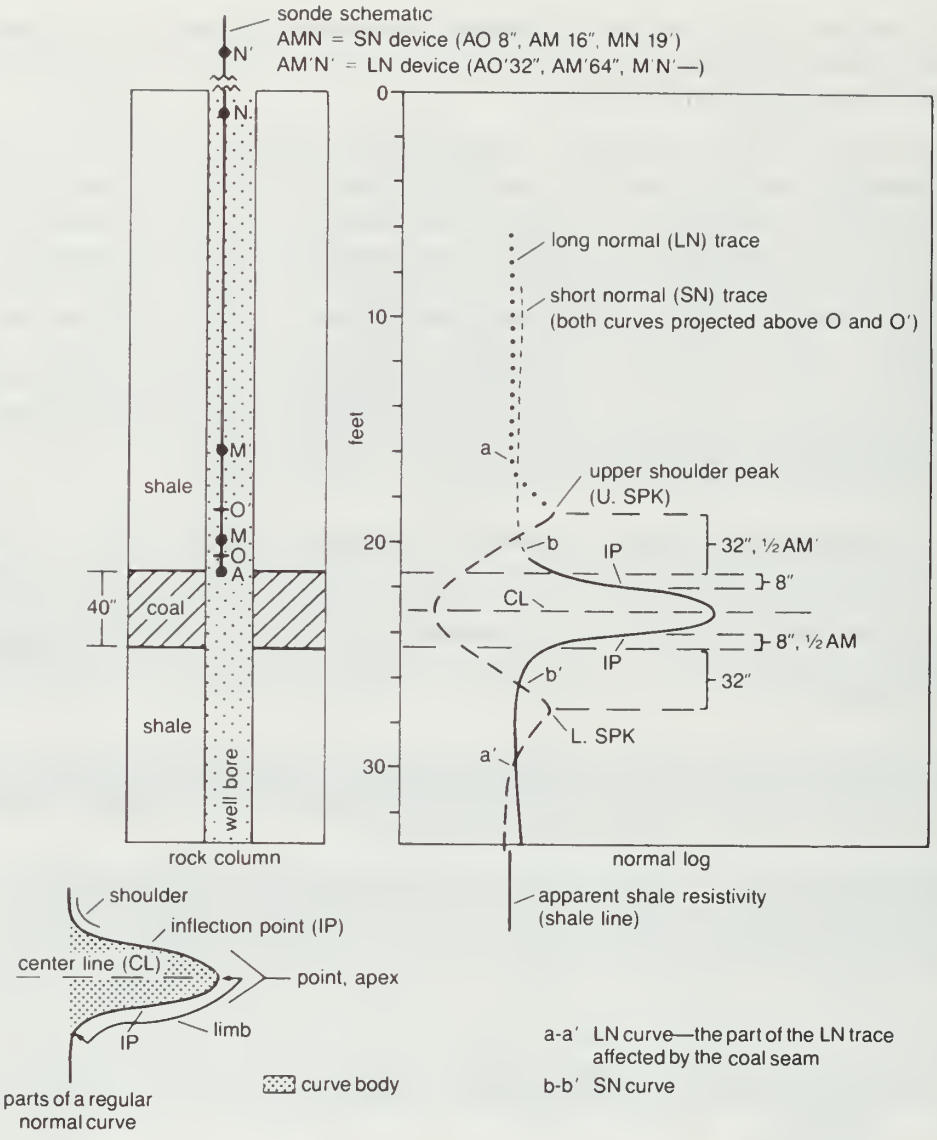

Figure 1 Idealized 16-inch and 64-inch normal curves for a thin coal seam between thick shale beds (see also fig. 4-4 in Schlumberger 1958; figs. 9-5, 9-6, and 9-8 in Guyod 1952b; and fig. 6 in Chombart ca. 1950).

CHARACTERISTICS OF NORMAL CURVES

Figure 1 depicts a well bore penetrating a thin (40-inch) coal seam between two shale beds. Two normal devices are being drawn up the well bore in the process of recording the two log traces. Electrode A is conducting current through the mud filling the well bore and into the surrounding rock. The short-normal (or AMN) device is measuring continuously the potential differences between electrode M and the uphole electrode N. The AM spacing is 16 inches; the measure point O (a reference point only and not an electrode) is midway between A and M, 8 inches from both. The long-normal (AM'N') device is identical to the short-normal device, except that the spacings between its electrodes are larger: its N' electrode is farther uphole than the N electrode, its AM' spacing is 64 inches, and its measure point O' is 32 inches from the A and M' electrodes. Other AM' spacings—56, 72, and 86 inches—have been used in Illinois. Most long-normal logs of this sort were made in the 1930s and 1940s and are identified on logs as

third-curve traces. (It is of no consequence that the measure points of the normal and lateral devices are at different places along a given sonde because the mechanical recorder that draws the several resistivity traces on a log registers all of them to the same vertical log scale.)

Figure 1 visualizes an idealized combination of stratigraphy, well bore conditions, and normal device responses. It reasonably exemplifies curves from logs of oil and gas wells penetrating coals in Illinois (Swann 1952). Assumptions made in figure 1 are: the well bore is filled with a freshwater mud, the bore is not caved and oversized, and the coal seam and clay shale bed have uniform composition and structure. The coal seam is highly resistive (i.e., less conductive than the adjacent beds), and the clay shale beds are conductive (more conductive than the adjacent coal).

The electrode configurations in figure 1 represent devices used on a Schlumberger sonde in the 1950s (Schlumberger Well Surveying Corporation 1949 1958, Hilchie 1979). Different well service companies used sondes with various combinations and spacings of normal and lateral devices. To measure and interpret a particular log, one always must take care to identify the kinds of devices and device spacings that produced its traces.

Normal devices produce symmetrical curves that ideally are centered on the centerplanes of the beds that form them. The peak deflection of a normal curve—whether regular or reversed—occurs when the measure point O of the device is opposite the centerplane of a bed (or of several thin beds that the device senses as a single unit). Note that normal devices do not make distinct curve features right at bed bases and tops. The inflection points and shoulder peaks indicating the base and top of a bed occur at one-half of a device's spacing inside the bed boundaries if the curve is regular and one-half spacing outside the bed boundaries if the curve is reversed.

Figure 1 illustrates the relationship of device spacing and bed thickness to the kind of curve formed. If the resistive bed is thicker than the spacing of the normal device, its curve deflects rightward, forming a single regular peak, as does the 16-inch short normal in the 40-inch bed. If the bed is thinner than the device's spacing, the middle of its curve deflects leftward, forming a curve resembling a W with the reversed peak between two shoulder peaks, as does the 64-inch long normal.

Certain features of normal curves can be used to locate the tops, bases, and centerlines of thin resistive beds, but seldom are all of these features present or well formed. On a reversed normal curve, the base and top of a resistive bed are indicated by the positions of its two shoulder peaks (fig. 1). The point of each shoulder peak is one-half the device's AM spacing outside the bed—one-half AM′, 32 inches (fig. 1). The shoulder peak associated with the base of a resistive bed is formed as the M′ electrode of the ascending device enters the bed. The shoulder peak associated with the top of a bed is formed as the A electrode leaves the bed.

On a regular normal curve (16-inch short-normal curve, fig. 1), the base and top of a resistive bed are indicated by the position of the inflection point on each curve limb. The inflection point is the point on a curve limb where the slope changes sign (where the curve goes from concave to convex). Each inflection point is one-half the device's AM spacing (8 inches for short normal, fig. 1) inside a bed's top or base. The inflection point that is one-half AM spacing above the bed's base is formed as the A electrode enters the bed. The inflection point that is one-half AM spacing below the top of the bed is formed as the M electrode leaves the bed. The inflection points are subtle features, often difficult to locate closely. They show up best on the less common large-scale normal logs (5-inch scale and larger) that record moderate deflections (midscale peaks) for resistive beds. Usually, inflection points are not visible on the more common, small-scale, 2-inch logs, especially if the resistive beds produce strong deflections

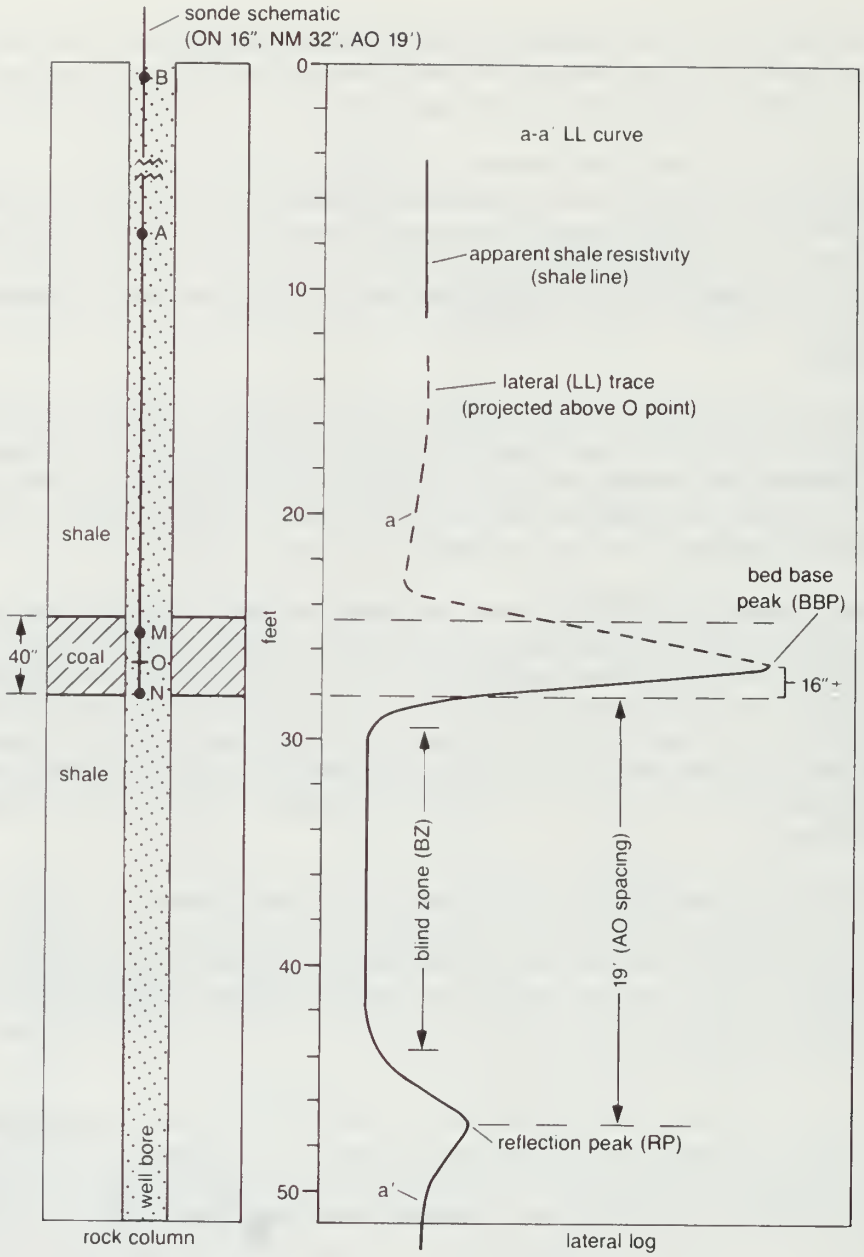

Figure 2 Idealized 19-foot lateral curve for a thin coal seam between thick shale beds (see also figs. 6-7 and 6-14 in Guyod 1952a, fig. 4-5 in Schlumberger 1958, fig. 6 in Schlumberger 1955, and figs. 10 and 10′ in Chombart ca. 1950).

(full-scale peaks) having limbs that are straight over much of their length. In any case, inflection points cannot be found on misshaped limbs of regular curves.

Several characteristics of normal device performance complicate the interpretation of logs. A reversed normal curve for a resistive bed resembles the trough response of a thin conductive bed. (Usually, the reversed curve's unusually low resistivity in its central deep trough and its characteristic shoulder peaks identify it. If both the long normal and short normal are reversed, the lateral curve for the bed gives a regular bed base peak response and shows the bed is resistive.)

An alternating series of conductive and resistive beds that range in thickness from less than normal (AM) spacing to nearly twice normal spacing can produce smooth, very rhythmic, wavelike peak-and-trough patterns that have few or no bed boundary markers and are difficult to measure.

A normal device does not reliably detect beds thinner than about one-fourth of its spacing. In a series of interbedded conductive and resistive thin beds that individually have thicknesses less than and little more than a normal device's spacing, the device is apt to sense several adjacent thin beds (e.g., a coal, shale, and limestone sequence) as a single unit and record one bed curve for the sequence. Inches-thick shale partings in a coal seam that could significantly decrease the minability of the coal and the estimate of its tonnage usually are not detected, even by the short normal.

Normal devices often produce vague log features. Deformations of regular curve limbs and the lack of well-defined inflection points and shoulder peaks have been mentioned. Lopsided regular curves are another problem. In such cases, a line bisecting the regular curve's point does not bisect the curve body. Typically, lopsided points are displaced upward 1 or 2 feet and are formed when the normal's uphole N electrode is passing through a resistive bed as its AM electrodes enter a resistive bed and record its peak. Another kind of vague feature is the small peak recorded by a resistive bed that is a little thicker than a normal's spacing. These small, often deformed, peaks are easy to overlook, particularly at small log scales (see fig. A1, feature a). They are often recorded because the thicknesses of the more interesting deep-minable coal deposits in the Illinois Basin typically fall within 1 foot of the most common, 64-inch AM′, long-normal spacing.

Appendix A discusses in detail the interpretation and measurement of normal curves recorded on two E-logs.

CHARACTERISTICS OF LATERAL CURVES

Figure 2 represents a lateral device ascending a well bore and displays the electrical log trace recorded as it passes through a thin (40-inch) coal seam lying between thick shale beds. As the sonde bearing the device is pulled up the hole, electrode A, part of current-generating circuit AB, is conducting current through the mud filling the well bore and into the surrounding rock. The potential difference between electrodes M and N is measured and the values recorded continuously as a lateral trace. The part of the lateral trace that is formed as the device's AMN electrodes pass through the coal seam is the lateral "curve" of the seam (fig. 2). Any given point on a lateral trace records the apparent resistivity measured by the device as its O measure point passed through the well depth shown on the log's scale for the point. (But keep in mind that the value measured does not represent a point or plane in the well bore and surrounding rock: it is the value obtained by measuring a not very definite volume of rock and well mud surrounding the device's electrodes.) The measuring electrodes M and N of the lateral device in figure 2 are 32 inches apart and the O measure point is midway between them—16 inches from the N (or bottom) electrode of the device. These measurements are typical of the Schlumberger lateral devices (Hilchie 1979, Schlumberger Well Surveying Corporation 1949 1958).

The spacing of a lateral device is the distance between the O measure point and the second electrode uphole from it. In figure 2, the spacing is 19 feet—the distance between the A electrode and O measure point. In other patterns of the lateral device, the second electrode uphole from the O point is either the M or the N electrode, but in all cases, the spacing of a lateral device is noted on an electrical log as the AO spacing. Several "short" and "long" lateral

spacings have been used by the petroleum industry. Long spacings are the rule in Illinois, 18 feet 8 inches and 19 feet being common and 24 feet being older and occasional.

Literature of Schlumberger Well Surveying Corporation (1949 1955 1958), Dresser Industries, Inc. (1982), and other well service companies and articles by Chombart (ca. 1950) and Guyod (1952a) describe the various lateral curve configurations that are produced by resistive and conductive beds ranging in thickness from several times AO spacing to fractions of it. Figure 2 illustrates a curve that can be produced under Illinois conditions by a thin resistive bed or coal seam 40 inches thick, or about one-fifth AO spacing. The curve generated by the lateral device is drawn as a solid line up to the point where the bottom (N) electrode is shown entering the coal seam. A dashed line represents the curve that will be formed as the device ascends farther uphole.

A lateral curve is not in itself symmetrical, nor is it symmetrical to the resistive bed that produces it. When the resistive bed is thin (by our term, less than one-half AO spacing), its lateral curve consists of three features: reflection peak, blind zone, and bed base peak. The resistivity values indicated by these features are always false: consistently low in the blind zone and high at the bed base peak and reflection peak.

A reflection peak is recorded on a log at the indicated depth of the sonde's O point as the uphole A electrode, 19 feet above the O point, enters the base of a resistive bed (coal seam, fig. 2). The resistivity of the reflection peak in figure 2 is not the resistivity of the shale, but a high, false reading. Similarly, a false depressed resistivity for the shale is recorded in the blind zone (or dead zone, as some writers call it). The blind zone is recorded on the log while the resistive bed is between the A and O electrodes. The more distinct blind zones and reflection peaks are recorded in shale sections (conductive beds) thicker than the AO spacing. Where resistive beds occur in the AO interval below a particular thin resistive bed, their blind zones and bed base peaks will be combined additively with the reflection peak and blind zone features generated by the high bed.

The bed base peak is formed at the O point as the N (or bottom) electrode enters the base of the bed. The bed base peak records the highest apparent resistivity of the bed. In ideal conditions, the apex of the bed base peak is 16 inches above the bed base—the ON distance—for the device configuration shown in figure 2. Several common conditions will shift a bed base peak up or down about 1 foot. Resistive beds within AO distance above the target bed can deflect the point of the bed base peak upward or create a compound curve with a displaced point. Borehole diameter, resistive bed resistivity, and mud resistivity affect the shape and location of a bed base peak slightly (Schlumberger Well Surveying Corporation 1955, Hilchie 1979). A few old Illinois lateral logs were made with inverted lateral devices, which produced upside-down curves with bed peaks related to the tops rather than the bases of resistive beds.

Lateral devices are better suited than normals to detect thin resistive beds (Schlumberger Well Surveying Corporation 1949 1958). They typically produce strong bed base peaks for thin resistive beds, even for beds less than 1 foot thick for which the normal curves are absent, weak, or reversed. Although lateral curves do not mark the tops and centerlines of thin resistive beds in any obvious way and are asymmetric in relation to the beds, their bed base peaks and reflection peaks can yield close locations of bed bases.

Appendix B describes the interpretation of lateral logs in more detail.

MEASUREMENT TECHNIQUES

Figures 3, A2, and B2 (see appendixes) illustrate the more common half-seam and whole-seam measurements that can be made on normal-lateral E-logs. An individual's experience and preferences and the characteristics of the E-logs used will determine which seam curve measurements are made, but some general recommendations apply in every case.

- All the curves for a seam should be examined and their various features identified. Above all, the spacings of the devices that made each log must be ascertained. A transparent template horizontally ruled with the common short-normal, long-normal, and lateral spacings in normal-lateral E-log relationships and scale (fig. 4) can speed up the initial examination because it eliminates much finicky drafting and measurement on the log being examined.

- The features of curves used for measurements should have definite, well-formed shapes. Peak features should have definite apices. The centerline of a spontaneous potential or normal curve should bisect both the curve body and its apex: a line bisecting a lopsided apex is not a curve-body centerline.

- Measurements should be made as precisely as possible. The 5-inch-scale "detail log" attached to the end of a 2-inch-scale normal-lateral E-log should be used if it includes the Pennsylvanian section. A log's horizontal footage rulings should be checked routinely for accuracy. Lines drafted for bed bases, bed tops, and centerlines must be parallel to each other and to the horizontal log rulings. (A transparent graph-ruled ruler is useful.) Engineer's scales are needed for close measurements. (On 2-inch-scale logs, 50-division-per-inch rulers yield measurements to the half-foot. On 5-inch-scale logs, 30-division or 60-division scales yield measurements to the third-foot.) It may seem unreasonable to recommend measurements accurate to fractions of feet to obtain apparent thicknesses only
accurate to 1 or 2 feet at smaller scales. However, close measurements demonstrate the reliability of the log and confirm which curve features define bed planes.

- To interpret what rock units a particular sequence of normal-lateral E-log curves represents, one should, if possible, continually compare the curves to geologic descriptions of the rock units in the same interval in nearby cores, outcrops, and mine faces.

- Bed thickness measurements should be consistent with the maximum-minimum thickness ranges indicated by reversed and regular normal curves.

Figure 3 reproduces 200 feet of the Pennsylvanian section of a normal-lateral E-log. The five thin, numbered resistive beds are the Herrin Coal (1), the Houchin Creek Coal (2), a coal or limestone bed (3), the Colchester Coal (4), and the Davis Coal (5).

Unit 1

The regular short-normal and reversed long-normal curves indicate that bed thickness is greater than 16 inches and less than 64 inches. The reflection peak (1c) to bed base peak (1a) equals AO + ON lateral device spacing and indicates bed base at ±225 feet.

The short-normal curve is lopsided because its N electrode 19 feet uphole is in the limestone bed at 196 to 204 feet. Its peak (feature e) is offset about 2 feet above the long-normal centerline. The short-normal inflection points are not distinguishable.

The lower long-normal shoulder peak is distinct and places the bed base at ±225 feet (the same as the bed base off the lateral). Long-normal feature 1d is on the centerline of the thin

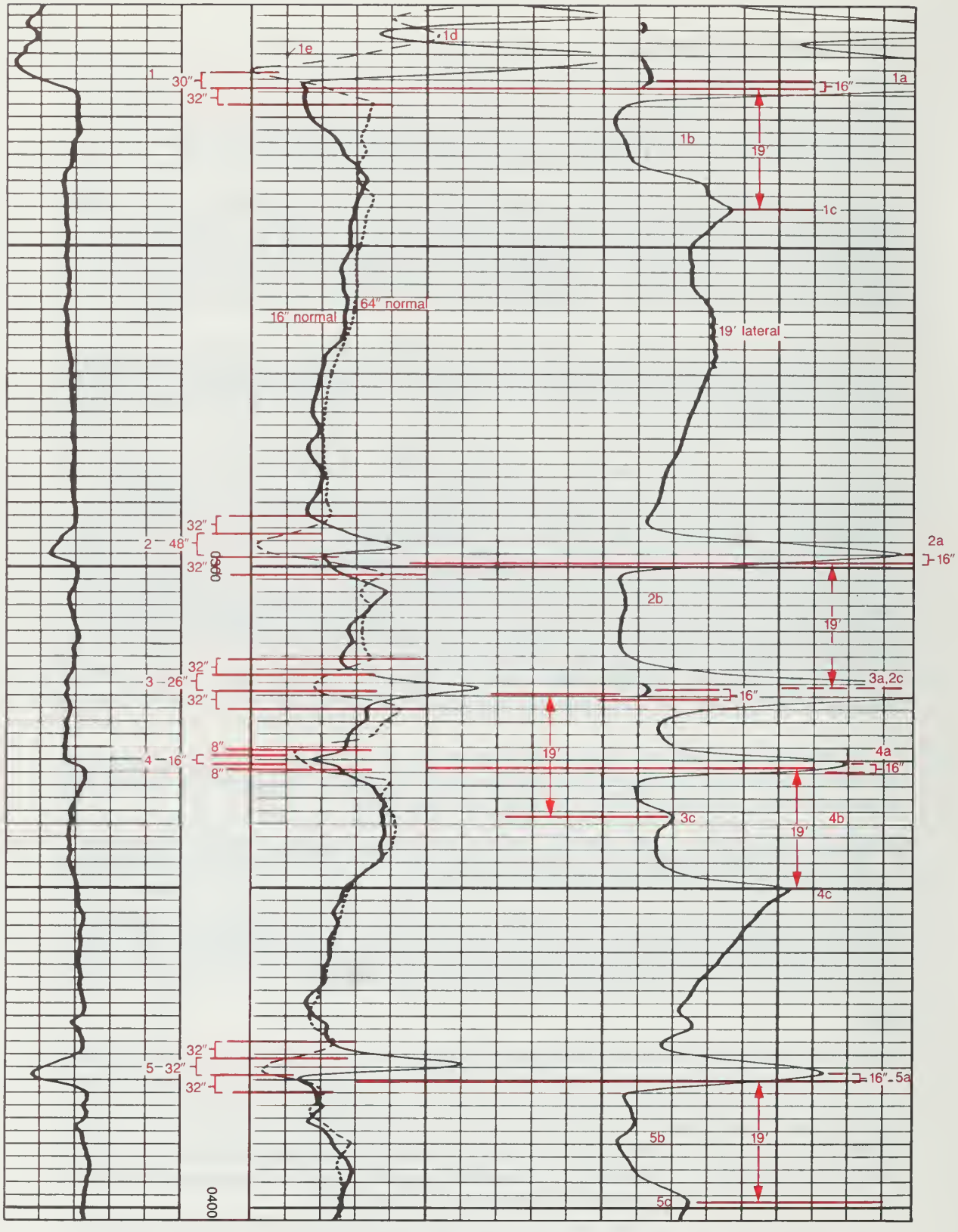

Figure 3 Thin-bed measurements from curves on a normal-lateral E-log (5-inch scale) (1957 Schlumberger Well Surveying Corporation log, Co. No. 2245, Sec. 10, T4S, R2W, Perry County, Illinois).

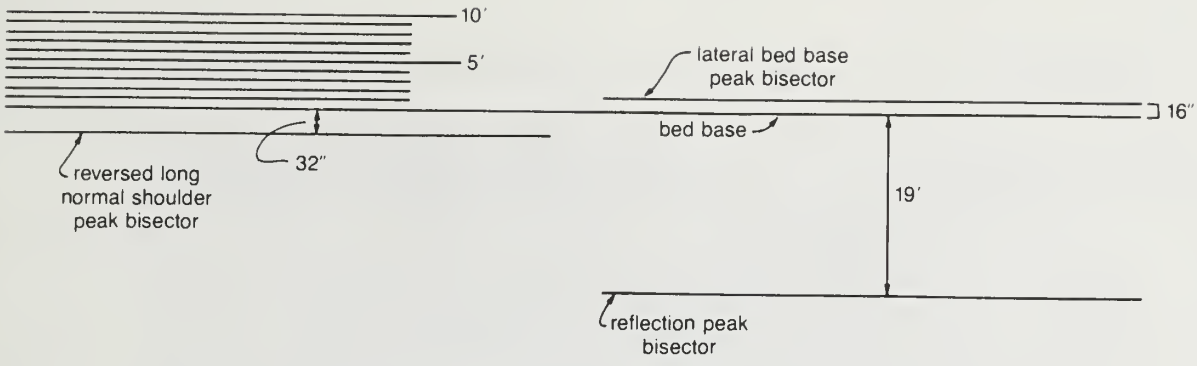

Figure 4 Transparent template pattern for examining normal-lateral E-logs.

shale (well marked by the spontaneous potential curve and the short-normal trough) between the Herrin and the limestone bed at 214 feet.

The measurement of 30 inches between the long-normal centerline and the bed base indicated by the long-normal shoulder peak yields a whole-seam thickness of 60 inches and seems preferable to other combinations because it is made from sharp features on the same curve. Measuring between the short-normal centerline and the long-normal shoulder peak, for example, gives a false bed thickness of about 120 inches—it contradicts the <64-inch thickness indicated by the reversed long-normal and the apparent thickness of the short-normal curve.

C. G. Treworgy (personal communication, ISGS, 1990) pointed out that using Hopkins' method, one can obtain a thicker estimate of about 72 inches from the short-normal curve. This estimate is consistent with data from five cored holes that penetrated 76 to 82 inches of coal within 1/2 mile to the west, north, and east of this well. It is not consistent with the <64-inch indication of the reversed long normal. No coal thickness data are available within 1 mile to the southwest, south, and southeast. This leaves open the possibility that coal thins 1 foot or more in a small distance, as it is known to do in the area. In an apparently equivocal situation, whether one credits the thicker estimate from the short normal or the thinner measurement from the long normal depends on the method followed.

Unit 2

The regular short normal and reversed long normal indicate bed thickness is greater than 16 inches and less than 64 inches. The lateral reflection peak (2c) is combined with the lateral bed base peak (3a) and is a dubious reference point. The lateral bed base peak (2a) + ON yields a bed base at ±299 feet 4 inches (~12 inches below the bed base from the long-normal shoulder peak).

The short-normal limbs are not visibly inflected. The long normal and short normal have the same centerline. (The 60-foot section uphole is shale and does not influence the uphole electrodes in a way that offsets the peaks.) The long-normal shoulder peaks at ±292 feet 0 inches and ±301 feet 4 inches yield a seam thickness of 48 inches (301 feet 4 inches – 292 feet 0 inches = **112** inches; 112 inches – 64 inches = ±48 inches).

Unit 3

Bed thickness is greater than 16-inch spacing and less than 64-inch spacing. The compound lateral peak (3a + 2c) is a dubious reference point. The reflection peak (3c) yields a bed base at ±320 feet (~8 inches below the bed base indicated by the long-normal shoulder peak).

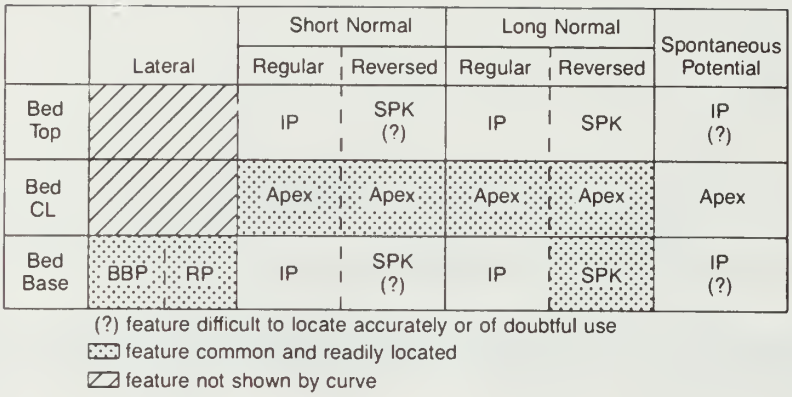

Figure 5 Features of normal-lateral E-log curves that indicate bed tops, centerlines, and bases. Abbreviations: CL, centerline; IP, inflection point; SPK, shoulder peak; BBP, bed base peak; RP, reflection peak.

The long-normal shoulder peaks at ±314 feet 6 inches and ±322 feet 0 inches are distinct features yielding a bed thickness of ±26 inches (322 feet 0 inches – 314 feet 6 inches = 90 inches; 90 inches – 64 inches = 26 inches).

Unit 4

Bed thickness is less than 16 inches—both normals are reversed. Lateral bed base peak (4a) + ON and reflection peak (4c) + AO do not define the same bed base and overlap about 1 foot.

The shoulder peaks of the reversed short normal at ±328 feet 6 inches and 331 feet 2 inches yield a bed thickness of ±16 inches (331 feet 2 inches – 328 feet 6 inches = 32 inches; 32 inches – 16 inches = 16 inches). A measurement at this scale is not meaningful. The long-normal and lateral responses to this very thin bed are distinct indicators in contrast to the reversed short normal, which might be mistaken for a clay shale parting between sandy and silty shale beds.

Unit 5

This bed is thicker than 16 inches and thinner than 64 inches. The reflection peak (5c) to bed base peak (5a) equals AO + ON and places the bed base at ±380 feet 0 inches. (The long-normal shoulder peak bed base is at ±379 feet 4 inches, about 8 inches higher.)

The long-normal shoulder peaks at 374 feet and 382 feet yield a seam thickness of ±32 inches (382 feet – 374 feet = 96 inches; 96 inches – 64 inches = 32 inches).

PROBABLE ACCURACY OF VARIOUS MEASUREMENTS

On an ideal normal-lateral E-log, the spontaneous potential, short-normal, long-normal, and lateral curves for a particular coal seam might record as many as 17 distinct and congruent features to mark the seam's top, centerline, and base (fig. 5). However, on an ordinary good normal-lateral E-log, the curves for a seam will bear scarcely half as many identifiable and precisely measurable curve features, and commonly the measurements made from several curve features to a seam plane will vary as much as 1 foot. Given such deficiencies, how does

Table 3 Types of thin resistive bed measurements in order of probable accuracy.

Type 1	Whole-bed (top to base) measurements made on the same curve with
	1 inflection points on regular short-normal curve
	2 inflection points on regular long-normal curve and shoulder peaks on reversed long-normal curve
	3 inflection points on spontaneous potential curve
Type 2	Half-bed (centerline to base or centerline to top) measurements made on the same curve with
	4 centerline and one inflection point of regular short-normal curve
	5 centerline and one inflection point (or shoulder peak) of regular (or reversed) long-normal curve
	6 centerline and one inflection point of spontaneous potential curve
Type 3	Half-bed (centerline to base or centerline to top) measurements made on two different curves with
	7 centerline to base (or top) with each plane located by congruent measurements from features on two different curves
	8 centerline to base (or top) with one plane located by a measurement from only a single feature

one decide which of several possible combinations of measurement best represents a seam's thickness? Table 3 lists most of the measurements that can be used to obtain seam thickness and ranks them from higher probable accuracy to lower.

Type 1 Measurements

Measurements made on the same curve are preferable to other types because doubling type 2 and 3 half-seam measurements to obtain whole-seam thicknesses doubles any error caused by measuring procedures and curve distortions. Measurements from the inflection points of short-normal curves are preferable to others because the short-normal device should define thin beds more accurately than a long-normal device. (Measurements from reversed short-normal curves are not listed because the unavoidable errors made in measuring seams less than 2 feet thick amount to so much of their thickness.) Although the inflection points of spontaneous potential curves are given a high rating, they are usually difficult to locate precisely on thin resistive beds, particularly on 2-inch logs. Also, where a limestone lies within 1 or 2 feet of a coal seam, the spontaneous potential often reads the two beds as one.

Type 2 Measurements

Well-formed base-marking features are more common on the spontaneous potential, short-normal, and long-normal curves than the top-marking features. Coal seams typically lie above conductive mudstone intervals and below intervals of marine sediment with resistive limestone beds and calcareous sediments. A lower mudstone-coal contact develops distinct seam-base features on a curve, but a limestone bed on or close above a coal often obscures or prevents formation of seam-top curve features.

Type 3 Measurements

Although this type is rated as less accurate than types 1 and 2, of necessity it is often used. Measurements from the lateral bed base peak or reflection peak or both often confirm the location of a base-indicating feature of the spontaneous potential, short normal, or long normal. Usually two of the apices of spontaneous potential, short-normal, and long-normal curves define a common seam centerline. Type 3 measurements work best on high-quality E-logs made after 1950 with more accurate recording equipment.

Sources of Inaccuracy

The analyses of the logs reproduced by figures 3, A2, and B2 demonstrate many of the typical problems associated with interpreting E-log curves and measuring them. Other influences need to be mentioned.

The ordinary log scales are always a problem. To spare expense, most oil producers in the Illinois Basin recorded the Pennsylvanian section of their wells only on the 2-inch scale, which renders 1 vertical foot as 1/50 inch on the log—an increment of about 0.5 mm, the width of a fine pencil line and the heavier log traces. Preferring to measure coal thickness in fractions of an inch, one reasonably settles for the closest foot at such scales.

Most of the normal-lateral E-logs were produced by equipment designed to log oil-well pay zones and not set up to measure thin beds and the thinner partings and splits in coal seams that can significantly affect mining operations and resource estimates. Logs made by various gamma ray, density, sonic, neutron, focused-current, and single-point electrode logs define coal seams more accurately than do normal-lateral E-logs (Bond et al. 1969).

The quality of normal-lateral E-logs varies greatly with age: post-1950 logs are much preferable to the older ones. Before 1950, a typical E-log in Illinois was run with spontaneous potential, short normal, and long normal, but lacked a lateral trace. Its traces tended to be rather smooth and generalized. Not only was the earlier logging equipment less responsive, but the logs were hand-drawn composites. One log was made as the sonde sank down the hole and a second was made as the sonde was pulled up. Then one log was traced onto the other. Naturally, the ascent-descent logging and the copying process somewhat altered curve registration and obscured details of curve features (King 1990). The inferior quality of the older logs probably accounts for Cady and other early workers concluding that E-logs were of little use for coal thickness estimates.

The quality of normal-lateral E-logs also varies in any period between logging companies. The procedures and equipment of some produced log traces lacking the fine and precisely recorded detail needed to measure and detect thin beds, particularly on small-scale logs.

Close-set, thin resistive beds common in the Carbondale Formation of Illinois cause distortions in bed curves. The Springfield and Herrin Coals commonly are overlain by interbedded thin shale and limestone beds—the limestone beds being spaced above the coals at distances near and equal to the different electrode spacings of the normal and lateral devices. In such cases, uphole electrodes of the devices often pass through limestones or coals just as their downhole electrodes measure target seams, and as a result, distorted target seam curves are recorded. Where a limestone sits tight on or a few inches above the coal, normal-lateral devices tend to sense one thick resistive bed for the two.

CONCLUSIONS

Hopkins' 1968 study established a technique since used by many workers to estimate coal seam thicknesses directly from normal-lateral E-logs. In practice, his method requires an observer to estimate the height of a vertical section through the thicker part of a short-normal curve's body near its base. Just where the section is taken—and the accuracy of the result—probably is not determined so much by short-normal curve inflection features, which often are unexpressed, as by near-intuitive decisions influenced by the individual's log interpretation skills, the amount of time available for the task, and knowledge of true coal thicknesses in cores, mines, and outcrops near the log location. This is not to fault the method,

which, given a skillful observer, is quick and demonstrably adequate for small-scale regional mapping.

The measurement methods compiled by this study have several advantages, particularly for studies of the 5-inch-scale logs of the Pennsylvanian section. Identifiable features of the normal-lateral E-log curves for a coal seam are used as reference points for measurements. Characteristics of the features and the measurements made from them can be used to interpret the log and to judge the reliability of the thickness measurements. Furthermore, the methods moderate interpreter biases that may arise from the thinner-than-bed appearance of normal curve bodies, the influence of known coal thickness data, and individual styles and skills.

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APPENDIX A INTERPRETATION AND MEASUREMENT OF EXAMPLES OF NORMAL E-LOGS

Only the resistive beds on the log in figure A1 are numbered. Cores from nearby coal test holes indicate that unit 2 is probably the Danville Coal, unit 6 is the Herrin Coal, and the rest are limestones. These units are interbedded with shales.

The long-normal device (AM′ 64 inches) made regular peak responses to units 1, 6, and 7, indicating that these beds are more than 64 inches thick. The small inconspicuous long-normal peak for unit 6 (feature a) indicates that the seam is only 1 or 2 feet thicker than 64 inches (the long-normal spacing). To miss this tiny feature is to risk mistaking the shale curve at feature b for a reversed long-normal peak and the oddly shaped peak of unit 7 (feature c) for its lower shoulder peak.

The long-normal response to unit 5 is a vague steplike curve that lacks the distinct features of either a regular or reversed normal curve. The curve may indicate that unit 5 is very little thicker than long-normal spacing.

Feature d is a reversed short-normal curve created by unit 2, a resistive bed thinner than the 16-inch spacing of the short normal. Slight deflections of the spontaneous potential and the lateral curves opposite the feature also indicate the bed's presence. (Feature e may be the lower shoulder peak of the reversed long normal for bed d because it occurs about 32 inches [1/2 the long-normal spacing] below feature d.) Misalignments between short-normal and long-normal centerlines are not unusual. Of all the numbered curves, only the short-normal and long-normal curves of 1 and 3 show good centerline alignments.

The regular short-normal and reversed long-normal curves of units 3 and 4 demonstrate that these beds are thicker than 16 inches and thinner than 64 inches.

Figure A2, a log from western Perry County, illustrates the responses of two normal devices to alternating thin and close-set resistive and conductive beds in a section including the Piasa

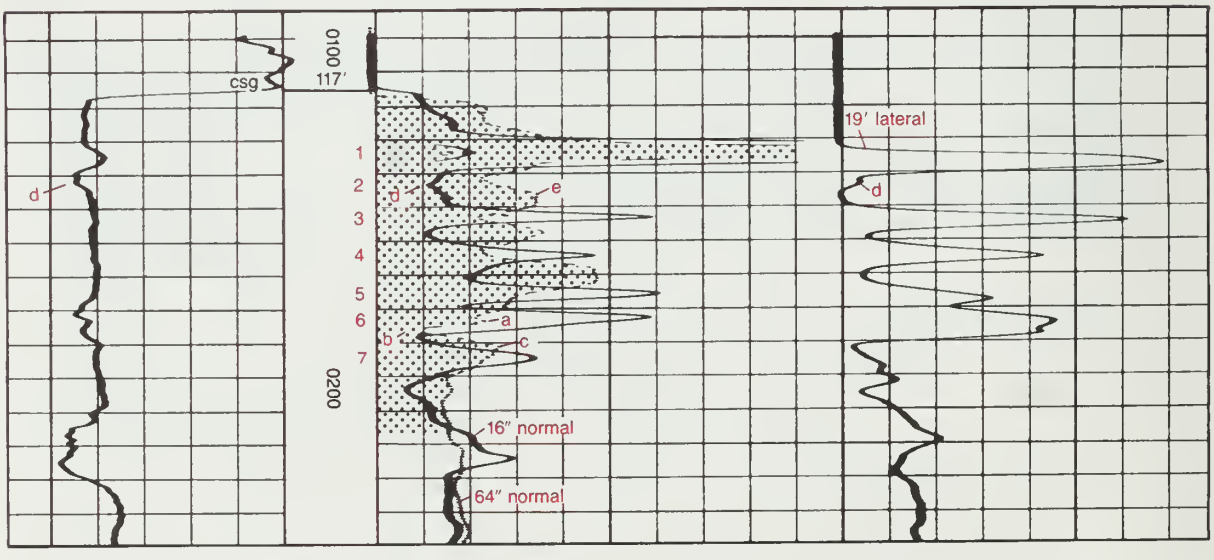

Figure A1 Features of typical long-normal and short-normal responses to thin resistive beds (2-inch scale: 2 inches = 100 feet) (1955 Schlumberger Well Surveying Corporation log, Co. No. 2147, Sec. 28, T4S, R3W, Perry County, Illinois).

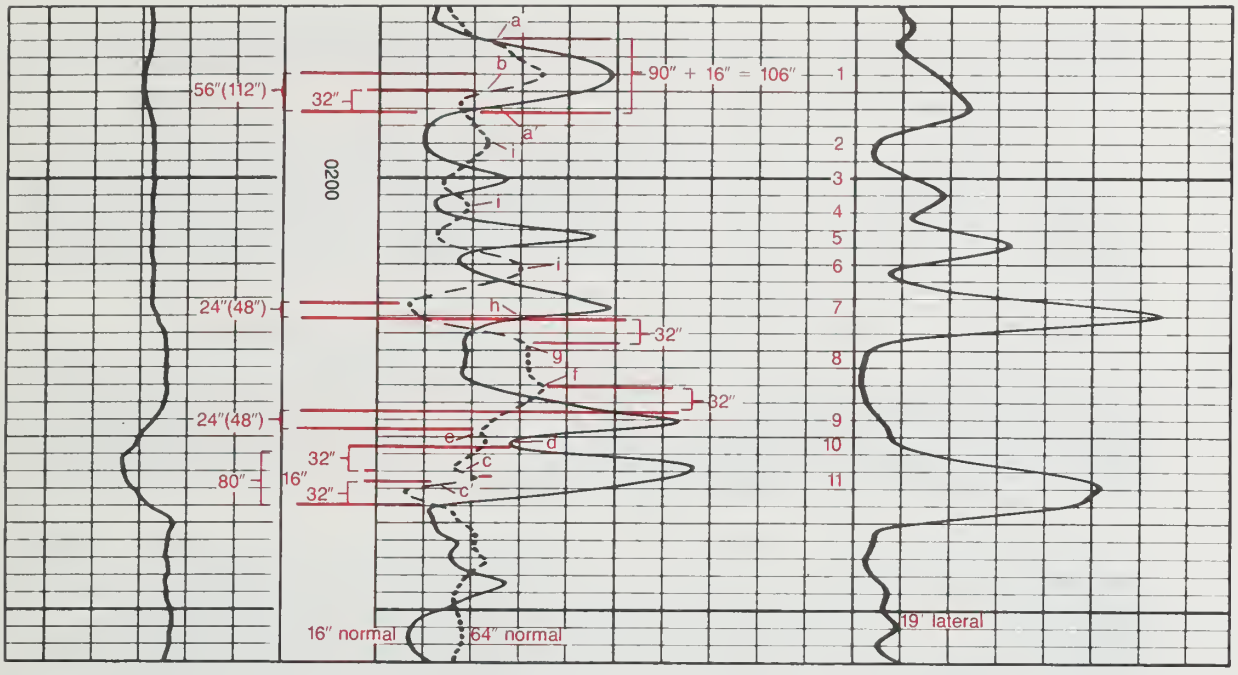

Figure A2 Thin-bed measurements from normal curves (5-inch scale: 5 inches = 100 feet) (1953 Schlumberger Well Surveying Corporation log, Co. No. 2514, Sec. 11, T4S, R3W, Perry County, Illinois).

limestone (unit 1) and the Herrin Coal (unit 11). It is typical of E-logs from the shelf area of the Illinois Basin, west of the Du Quoin Monocline. Units 2, 4, 6, 8, and 10 are shaly mudstones. Units 3, 5, 7 and 9 are limestones.

Unit 1, the Piasa Limestone, has a symmetrical, well-shaped short-normal curve. A line bisecting its point bisects the curve body and the limbs of the curve have visible inflections (a, a′). Larger log scales such as this widen the curve bodies and reveal their inflections better than the smaller scales, which thin the curves.

The short-normal inflection points (a, a′) occur somewhere in the middle third of the curve's limbs, 90 inches apart at the points indicated. The long normal of unit 1 has an irregular upper limb, but the lower limb shows an inflection point at b or near it. The apparent bed thickness measured from the short-normal inflection points is 106 inches (90 inches + 16 inches, the short-normal spacing). Thickness measured from the long-normal inflection point and centerline is 112 inches (inflection point to centerline = 24 inches + 32 inches [1/2 long-normal spacing] = 56; 56 inches × 2).

The 6-inch difference between the short-normal and long-normal measurements probably results from uncertainty about the exact location of all the inflection points. In addition, cumulative and multiplied errors in measurement may have occurred because a 5-inch-scale log can be read only to within about 4 inches. In this case, the short-normal measurement is preferable to that of the long normal because an unmultiplied measurement is used and the shorter 16-inch spacing more closely defines bed boundaries. Bed top (to the nearest foot) is 184 feet; bed base, 193 feet.

Unit 11, the Herrin Coal, has a lopsided, regular short-normal curve: a line bisecting its point does not bisect the curve body. The short-normal peak is about 1 foot above the long-normal peak. A normal device records an upwardly deflected peak such as this when its downhole (M)

and uphole (N) electrodes are both in resistive beds. In this instance (assuming a sonde configuration common in the 1950s; Hilchie 1979) as the M electrode passed through the coal, its N electrode 19 feet uphole from M would have passed through unit 7, a limestone.

The thickness of unit 11 is best measured from the small, regular long-normal curve. The range of probable locations of the long-normal inflection points (points c, c′) are close together on the curve's short limbs. In contrast, the locations of the short-normal inflection points are uncertain because the curve's lower limb is convex downward and the upper limb is quite straight (the upper inflection point apparently is located somewhere in the middle third of the limb). Furthermore, the lopsided short-normal peak does not establish a bed centerline.

The long-normal curves limbs are short and straight, but assuming that the inflection points (c and c′) are at the midpoints of the limbs yields a minimum thickness of 16 inches between them. The apparent bed thickness is 80 inches (16 inches + 64 inches long-normal spacing). Bed top (to the nearest foot) is about 232 feet, and bed base, 238 feet.

It is difficult and impractical to make very close measurements of the alternating thin conductive and resistive beds between units 1 and 11. The normal curves show few distinct bed base and top markers—centerline features of the limestone and shale units dominate the sinuous wavelike pattern. For example, resistive beds 3, 5, 7 and 9 are all thinner than the long-normal spacing and therefore do not show the little, readily measured regular long-normal peaks; and all but 7 and 9 are too close together to show reversed long-normal shoulder peaks. The limbs of most of the regular short-normal peaks are quite straight, and their inflection points occur in long lengths of the limbs between their points and shoulders. (The upper limb of unit 9's short normal is concave upward and lacks inflection.)

Short-normal and long-normal responses indicate that limestone units 3, 5, and 7 are thicker than 16 inches and thinner than 64 inches. Unit 10 is a thin conductive shale bed that separates the Herrin Coal and the Brereton Limestones (unit 9).

Feature e on the long-normal curve of unit 9 appears to be a very small reversed peak representing the centerline of unit 9. (Note that the distance between e and the long-normal peak of unit 11 is the same as the distance between the regular short-normal peaks of units 9 and 11.) Feature f appears to be a long-normal shoulder peak and, if it is, marks the top of unit 9, 32 inches (1/2 long-normal spacing) below the shoulder peak. Measuring from this bed top to feature e, the presumed centerline marker, yields a half-bed measurement of 24 inches and a whole-bed measurement of 48 inches.

Measurements from features of the long-normal curve for unit 7 yield a thickness of 4 feet for the bed. Feature g is the lower shoulder peak of the reversed long-normal curve and measuring 1/2 long-normal spacing up locates the bed base line (which coincides with the bed base line obtained by measuring 1/2 short-normal spacing down from the probable inflection point (h) on the lower limb of the short normal). The long-normal bed base to long-normal centerline measurement is 24 inches.

Note that unit 8 is the only shale interval in the column sufficiently thicker than the 64-inch long-normal spacing to enable the device to produce long-normal shoulder peaks. The low peaks labeled i mark the centerlines of shale units 2, 4, and 6 and clearly illustrate that normal devices produce curves strongly tending to be symmetrical with the centerlines of thin conductive and resistive beds.

APPENDIX B INTERPRETATION AND MEASUREMENT OF EXAMPLES OF LATERAL E-LOGS

The resistive beds indicated by the log's normal and lateral traces are numbered (fig. B1). Where distinguishable, three lateral curve features are identified for these beds: bed base peaks are labeled a; blind zones, b; and reflection peaks, c. A bracket spans the part of the lateral trace that constitutes the identifiable curve for a particular bed. On this log, a bed base peak ideally would be AO + ON distance (19 feet + 16 inches) above its companion reflection peak.

The log can be divided into four sections on the basis of the lateral trace's textures (its various roughnesses and curve amplitudes). Two sections—from 100 to 180 feet and from 260 to 310 feet—are essentially the same. The normal and lateral devices measured conductive silty shale sections and a shale coarsening upward to sandstone from 150 to 100 feet. The normal and lateral traces are near parallel, relatively smooth, and record similar resistivities. Lateral traces do not exhibit very distinctive features in conductive units several times thicker than AO spacings.

In contrast, the lateral trace sections between 180 and 250 feet (1a-5c) and 310 and 480 feet (9a-15c) are rough-textured and characterized by long, sharp bed base peaks (which appear to nearly conform to the normals' regular peaks) and by numerous secondary features (which hardly conform to the normals at all).

Section 9a-15c is about 85 to 90 percent silty shale with thin interbedded sandstones. The remainder of the section consists of coal and limestone beds that form the regular short-normal peaks and the lateral bed base peaks. Local core records indicate that these thin resistive beds, if detectable on the E-log, are usually 1 or 2 feet thick and are absent or only a few inches thick in sections in which E-logs did not detect them. Most of the limestones lie close above the coals, and the coal-limestone units are separated from each other by thicknesses of shale one or two times the lateral's AO spacing, 19 feet. Given this wide separation, the lateral device recorded distinct blind zones and reflection peaks for units 9, 12, 13, and 15. Not all of these features are identifiable for units 10, 11, and 14 because the device compounded them with the features of other curves and thus obscured them.

The curves for units 13 and 14 are correlated with the Davis and Murphysboro Coals, and each curve is probably a response to a single bed. However, local core tests and the different curves for units 9, 11, and 12 themselves demonstrate that the devices sometimes read several beds together to form a single curve. Bed base peaks 11a and 12a indicate that at least two thin resistive beds are present in the interval 360 to 370 feet, although the spontaneous potential displays only a single curve and the long normal an apparently single reversed curve. The short normal indicates that as many as four resistive units may be present at 361, 363, 365, and 370 feet. Unit 9 is correlated with the Houchin Creek Coal and the lateral bed base peak and long-normal reversed curve seem to indicate a single bed is present. However, the two spontaneous potential peaks at 318 and 321 feet hint the presence of several thin beds—a limestone or a split coal or both—known from local core test borings.

The lateral trace in section 1a-5c is much different from that in section 9a-15c. Over half of the 70 feet in the section is composed of resistive limestone beds and coal seams. The shale intervals between these beds are fractions of the AO spacing and so only unit 6 has all three lateral features—a bed base peak, blind zone, and reflection peak—distinct enough to identify. Although the normal curves define eight resistive beds in the section, the lateral bed base peaks only show five of them plainly (units 1, 2, 3, 4, and 6). Because so many secondary lateral features are missing, the lateral trace for the section is generalized and resembles the

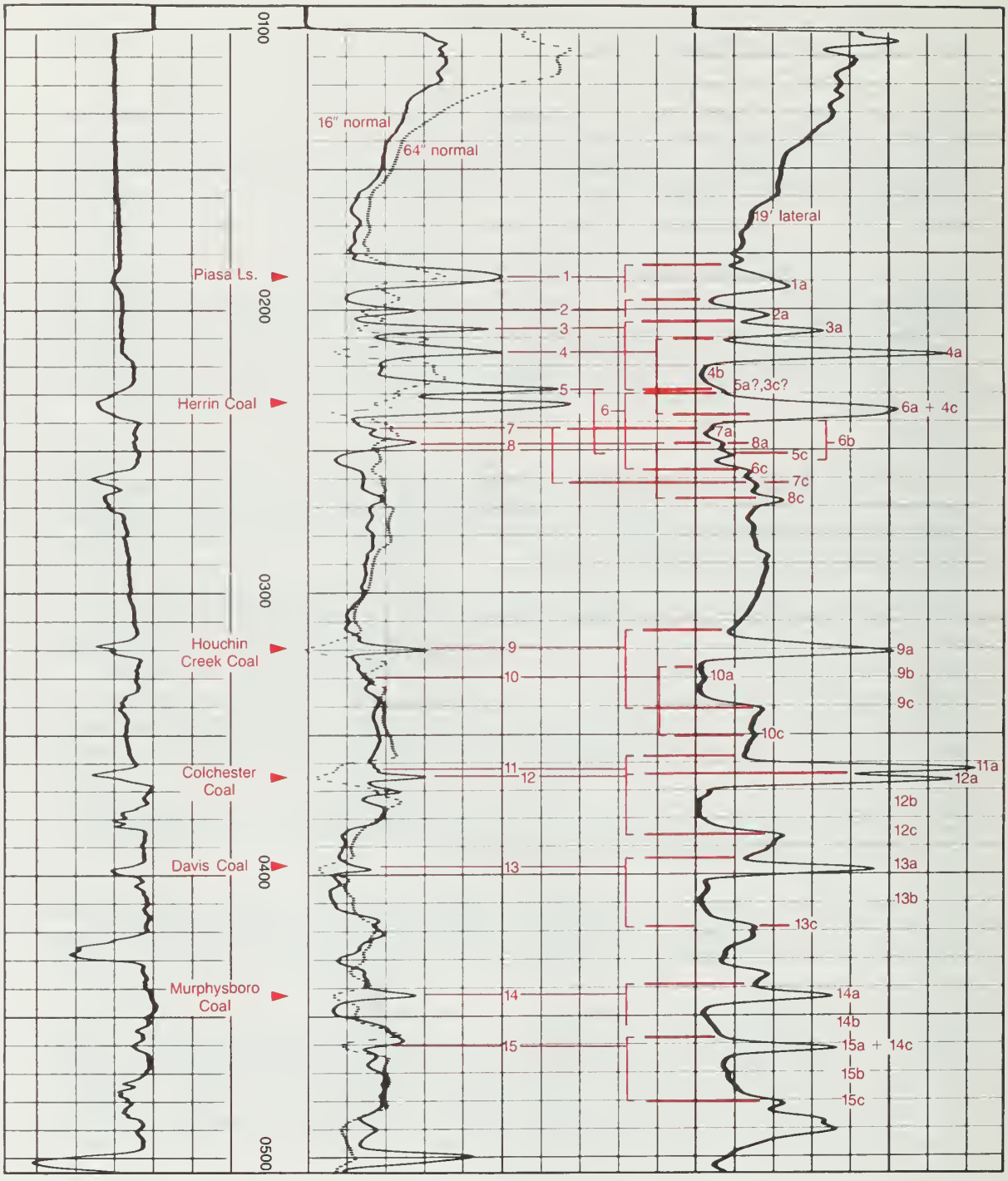

Figure B1 Features of typical lateral responses to thin resistive beds (2-inch scale) (1953 Schlumberger Well Surveying Corporation log, Co. No. 2514, Sec. 11, T4S, R3W, Perry County, Illinois).

short-normal trace. (Note that the short-normal and long-normal curves for the Herrin Coal, unit 6, are both regular, indicating that the coal is >64 inches thick.)

Figure B2 is the 9a-15c section of figure B1 at a 5-inch scale. The same numbers label the resistive beds and lateral curve features on both figures. Figure B2 illustrates the

measurements made from lateral reflection peaks and bed base peaks to locate the bases of the units and compares these measurements with measurements made from the spontaneous potential, short-normal, and long-normal features that also locate bed bases. Measurements of bed bases made from the spontaneous potential, short-normal, long-normal, and lateral curves for six of the seven units shown varied from 0 to 12 inches for a given unit and the average variance was 7 inches. These mismatches are inherent products of the logging and recording devices. Though as small as can be expected and hardly visible on a 2-inch-scale log, they are significant at larger scales, especially if they are doubled by doubling half-seam (centerline to bed base) measurements to obtain whole-seam thicknesses.

The main points for each unit are summarized below.

Unit 9 The lateral features are distinct; reflection peak (9c) to bed base peak (9a) equals AO + ON (19 feet + 16 inches), placing the bed base at ±322 feet 4 inches. The apparent spontaneous potential inflection point indicates a bed base at 322 feet. The long-normal shoulder peak indicates a bed base at ±321 feet 8 inches. Range of measurements: 8 inches.

Unit 10 Possibly a slightly resistive thin bed is weakly indicated by the congruence of measurements from the short-normal regular curve, the long-normal shoulder peak, and the little features that appear to be a lateral bed base peak (10a) and reflection peak (10c). (The bed base peak 10a is suppressed by the blind zone 9b.) The reflection peak to bed base peak equals 19 feet + 16 inches, placing the bed base at ±331 feet 4 inches. The apparent long-normal shoulder peak places the bed base at ±300 feet 8 inches. Range of measurements: 8 inches.

Unit 11 The distinct lateral bed base peak (11a) indicates possible bed base at ±363 feet 8 inches. A very weak regular short-normal curve at 362 feet is the only other indication of the bed's presence.

Unit 12 The lateral has distinct features. The reflection peak (12c) to bed base peak (12a) equals 19 feet + 16 inches, placing the bed base at ±367 feet 4 inches. The apparent short-normal inflection point at 366 feet places the bed base at ±366 feet 8 inches. Range of measurements: 8 inches.

Unit 13 The lateral features are distinct. The reflection peak (13c) to bed base peak (13a) = 19 feet + 16 inches, placing the bed base at ±399 feet 8 inches. The apparent spontaneous potential inflection point indicates a bed base at ±400 feet. The apparent short-normal inflection point places bed base at ±399 feet 4 inches; the long-normal shoulder peak places it at ±399 feet. Range of measurements: 12 inches.

Unit 14 The lateral bed base peak (14a) and blind zone (14b) are distinct, but reflection peak (14c) is compounded with the bed base peak of unit 15. The bed base peak depth minus ON spacing (16 inches) yields a bed base depth of ±244 feet 4 inches. The apparent short-normal inflection point and long-normal shoulder peak indicate the same bed base depth. Range of measurements: 0 inches.

Unit 15 The lateral features are distinct, but the reflection peak (15c) to bed base peak (15a) distance = ±19 feet 6 inches (10 inches ± less than AO + ON spacing) because the bed base peak (15a) is a little displaced by being compounded with reflection peak (14c). Measuring from reflection peak (15c) places the bed base at ±462 feet. The apparent spontaneous potential inflection point also places the bed base at ±462 feet. The long-normal shoulder peak places the bed base at ±461 feet 6 inches. Range of measurements: 6 inches.

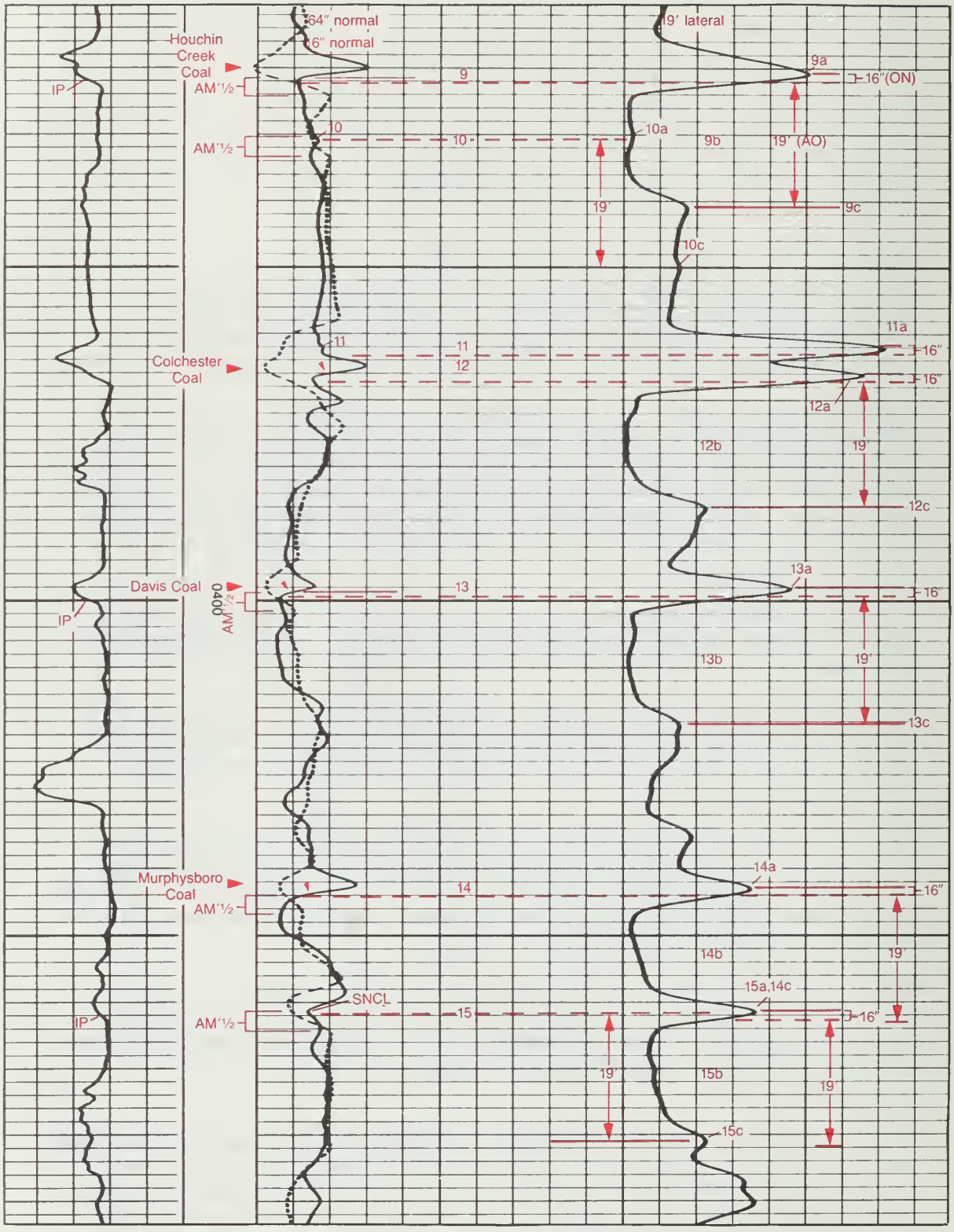

Figure B2 Thin-bed measurements from lateral curves (5-inch-scale).